Chapter 5
Determining Flood Flows by Precipitation-Runoff Analysis Methods

5-1. Introduction

Detailed hydrologic modeling is usually required for flood damage reduction studies. This area of hydrologic engineering, along with river hydraulics, normally takes the bulk of time and money in a study. This effort requires determination of how to subdivide the watershed to give required hydrologic information at points of interest, to develop the precipitation, loss, runoff, discharge, and routing information, and to calibrate and verify the model. Detailed modeling usually takes place during the feasibility phase. This chapter describes the various components of the hydrologic modeling performed.

5-2. Watershed/Subbasin Delineation

Delineation of the watershed into subareas to determine discharge information was discussed in paragraph 3-3. The study team must also participate by defining their information needs during this process. Location of damage reaches, potential flood damage reduction measures, political boundaries, and other items may cause further modification subareas to provide the necessary hydrologic data.

5-3. Analysis Approaches

a. General. The two main methods for determining flood runoff can be described as single-event analysis or continuous simulation, as illustrated in Figure 4-6. The former refers to determining the runoff from a single storm-flood event (the flood of 1986 or the 2-percent chance hypothetical flood). The main problem with this technique is a lack of knowledge of the antecedent soil moisture, especially for hypothetical floods. Assumptions as to wet or dry soil conditions may have a significant effect on the corresponding runoff.

b. Continuous simulation. The continuous simulation technique overcomes this problem as all periods of streamflow (droughts, floods, and all events in between) are simulated. This process is much more satisfactory in that more of the streamflow process is analyzed, but continuous simulation computer models are generally more data intensive and time-consuming to operate than event models. A lack of knowledge of other hydrologic variables needed for continuous models (evaporation, interception, subsurface and groundwater flow, etc.) may cause the results to be no more and perhaps less accurate than those of the single-event model. Continuous simulation models are often used where agricultural flood damage is extensive, because the time of year in which the flood occurs is important for damage calculations. Also, agricultural flood damage analysis may be required for relatively frequent events, such as the once- or twice-per-year flood. A flood this frequent is not usually suitable for event modeling.

c. Single-event analysis. Single-event models are typically used in urban flood damage analyses, since time of year is generally not important and the project design is for a rarer frequency, like the 1-percent chance flood. This publication will address only the hydrologic analysis related to a single- event model.

5-4. Precipitation/Runoff

Each subarea contributes a discharge hydrograph to the water moving throughout the overall watershed. Runoff from the several subareas is combined to yield the total discharge hydrograph at the outlet. Subbasin characteristics used to compute runoff include: rainfall, losses, transforms, and base flow.

a. Precipitation. Precipitation is atmospheric water in all its many forms. Flood reduction studies are primarily concerned with rainfall, with snowfall/snowmelt also of concern in certain regions of the United States. Rainfall is also further defined as being historical (recorded) or hypothetical.

(1) Historical rainfall. The engineer requires historical or actual rainfall for one or more storm events that produced flooding in the study watershed. The purpose of this historical rainfall is to calibrate the overall hydrologic model, ensuring that the model's output is representative of the basin. The actual rainfall that occurred over the study watershed produced a flood that was measured at one or more gages, or that reached heights that were remembered by local residents and then surveyed to determine high-water mark elevations. Rainfall input is used by the hydrologic model to produce flood hydrograph output at a gage site or a water surface elevation at a point of a known high-water mark. If the model's output is reasonably close to known discharges or water surface elevations, the model is considered to be calibrated and ready for use in developing discharge-frequency relationships. Historical rainfall for several actual storm-flood events would be desired, with the rainfall time sequence also being necessary. Depending on the size of the

watershed, incremental rainfall values ranging from 5-minute intervals to 24-hr increments would be necessary. Figure 5-1 shows an example of historic rainfall for application to a hydrologic model.

(2) Frequency rainfall.

(a) Hypothetical rainfall is required to determine discharge hydrographs for specific flood frequencies. Hypothetical rainfall is taken from past studies of the NWS, with Technical Publication (TP) 40 (NWS 1961), TP 49 (NWS 1964), and National Oceanic and Atmospheric Administration (NOAA) HYDRO-35 (NWS 1977) being the sources of these data for the 35 states east of the Rocky Mountains. The other 13 states in the continental United States have individual state atlases (NOAA 1973) to give the detailed information required in mountainous terrain. Alaska (NWS 1963, 1965a) and Hawaii (NWS 1962, 1965b) also have guidance specific to those states. Figure 5-2 gives an example of the type of information in NWS TP 40.

(b) Rainfall information is extracted at the location of the study watershed for each duration for a given frequency. The rainfall is incremented to determine depth in each time period, adjusted to reflect storm occurrence over an area rather than a point, and arranged in an appropriate pattern. An example of the adopted storm pattern for a given frequency and watershed is shown in Figure 5-3. Each frequency desired, from 50- through 0.2-percent chance exceedance storms, is developed in a similar fashion. Six or seven separate frequency storms are often required to give sufficient points to determine the resulting discharge-frequency curve with hydrologic modeling.

(3) Standard project storm.

(a) The hypothetical Standard Project Storm (SPS) is generated using a standard procedure (USACE 1965) for areas east of 105 deg longitude. For western areas, SPS's are normally generated by adjusting and transposing rare observed events to the study area from hydrologically and meteorologically similar areas. An example of an SPS, arranged for appreciation, is shown in Figure 5-4.

(b) The SPS is used to develop the Standard Project Flood (SPF). The SPF is the flood that can be expected from the most severe combination of meteorologic and hydrologic conditions that are considered reasonably characteristic of the region. The primary application of the

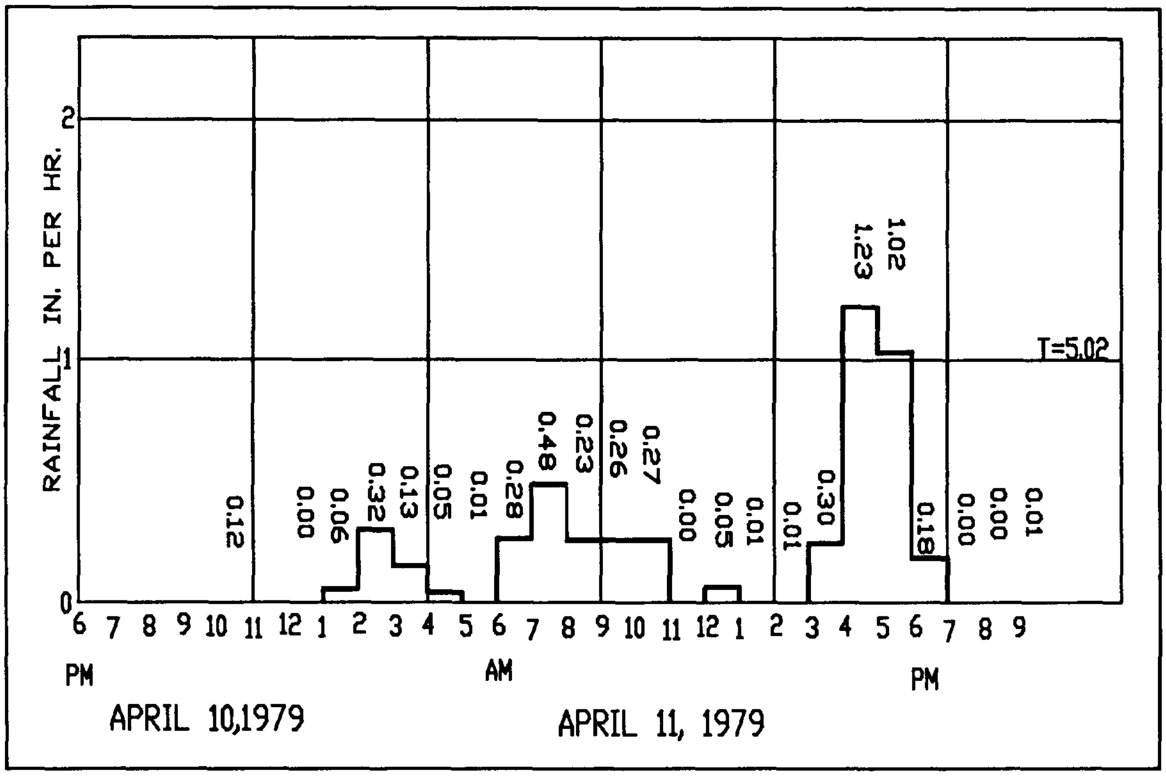

Figure 5-1. Example of historic rainfall

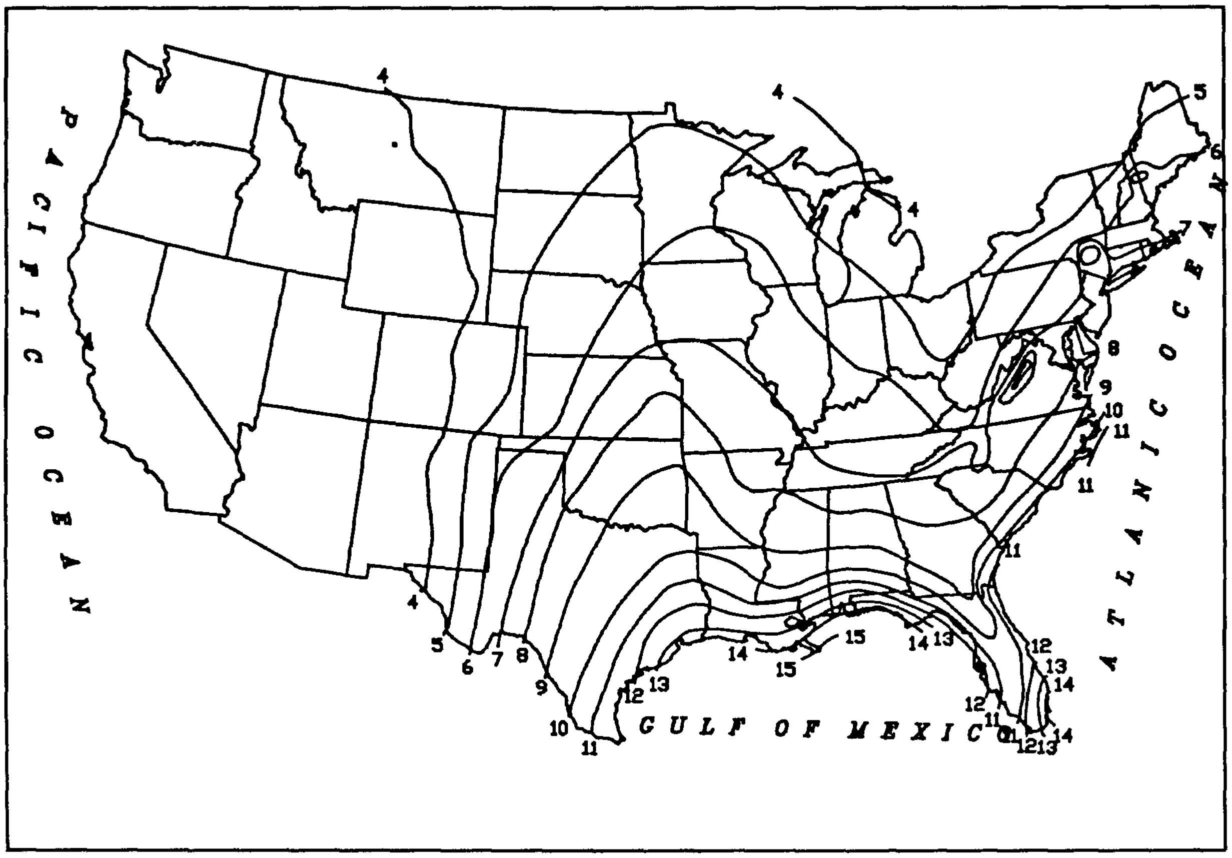

Figure 5-2. 100-year, 24-hr-duration rainfall map

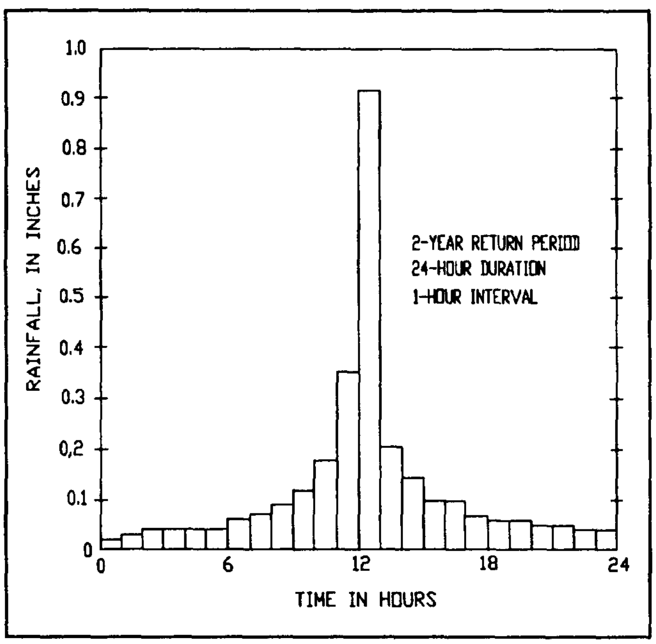

Figure 5-3. Typical time distribution for a hypothetical storm

SPF is to evaluate the performance of projects for an extreme event. Although a specific frequency cannot be assigned to the SPF, a return period of a few hundred to a few thousand years is commonly associated with the event.

(4) Probable maximum storm. This hypothetical event is normally required when dams and reservoirs are under consideration. Failure of a dam by overtopping could be a catastrophe for which no risk of failure would be allowed. Consequently, the Probable Maximum Storm, or PMS, (NWS 1982) is used for dam and spillway design to ensure that there is essentially no risk of design exceedance. Figure 5-5 shows a PMS arranged for use in a hydrologic model. The PMS is based on meteorologic studies of potential water in the atmosphere under the most extreme conditions.

(5) Snowfall/snowmelt.

(a) Snowfall is important in mountainous regions and in the northern portions of the United States. Unlike

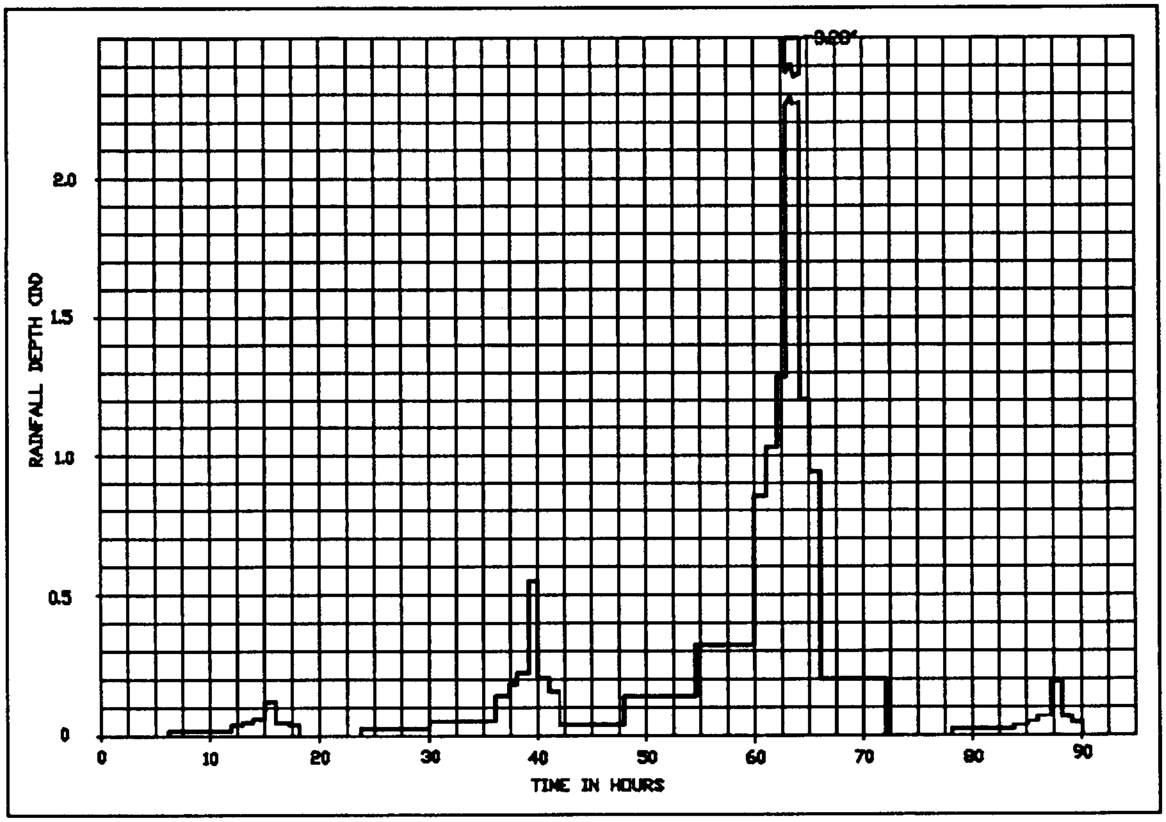

Figure 5-4. SPS arrangement

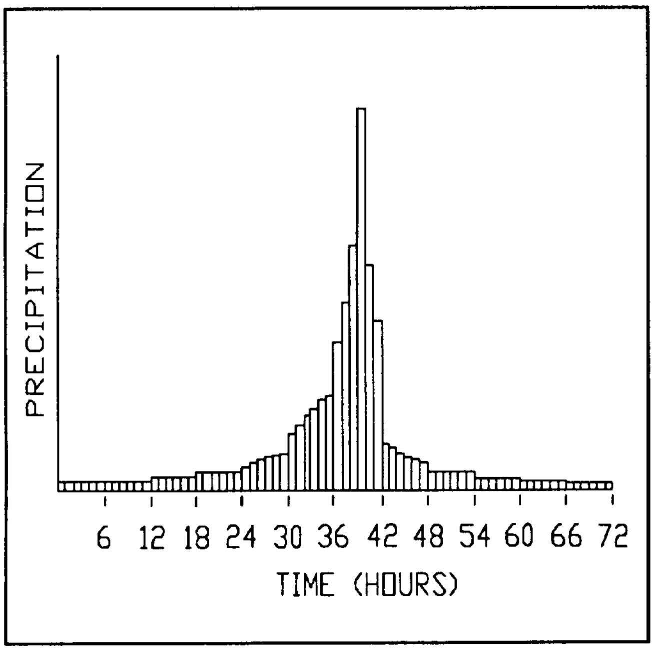

Figure 5-5. Probable maximum storm arrangement

rainfall events, snowfall can accumulate throughout the winter as a snowpack, which melts when warmer weather occurs. Therefore, the important variables for snow are: depth of snowpack and corresponding water content, air temperature, and topographic elevation. The last variable is important because the air temperature decreases with increasing elevation, and most air temperature monitoring gages are located in lower elevations. Depth of snowpack is monitored by physical measurements or by remote telemetry, with the corresponding water content determined.

(b) Snowpack information is critical for reservoir operation or structures receiving meltwater runoff, which includes most of the reservoirs in the western United States. Flood studies involving snowmelt are based on recorded data when available. When snow data are not available, it may be estimated by knowing rainfall and air temperatures, and converting to an estimated snowfall. No hypothetical basis is available for determining a synthetic snowmelt event.

b. Losses.

(1) General. Many methods are available for determining losses during a rainfall-runoff event, ranging from quite simple to very complex. For an event-type analysis, loss rates have been estimated using the uniform and initial method, the U.S. Soil Conservation Service (SCS) Curve Number method, the Horton technique, the Green-Ampt procedure, the exponential method, etc. (USACE 1990a). For a continuous simulation analysis, loss rate estimates could range from a simple runoff coefficient to a complete soil moisture accounting system.

(2) Adjustment of loss rates. The appropriate method is largely up to the judgement of the hydrologic engineer. Since the loss rates during a runoff event are not known, loss rates may be adjusted during the calibration analysis to allow a better reproduction of the known hydrograph or high-water marks by the model. Loss rates may also be adjusted depending on the storm severity, since the same loss rate would not be expected for a 50-percent chance (2-year) storm as for a 1-percent chance (100-year) storm. A rare storm is typically one in a series of events, which tend to increase the soil's antecedent moisture level and the corresponding runoff. Consequently, loss rates during a rare event would be expected to be less than a more common storm event. Loss rate adjustment is one way in which the argument in favor of continuous simulation models may be partially addressed. Figure 5-6 gives examples of simple loss rate accounting procedures.

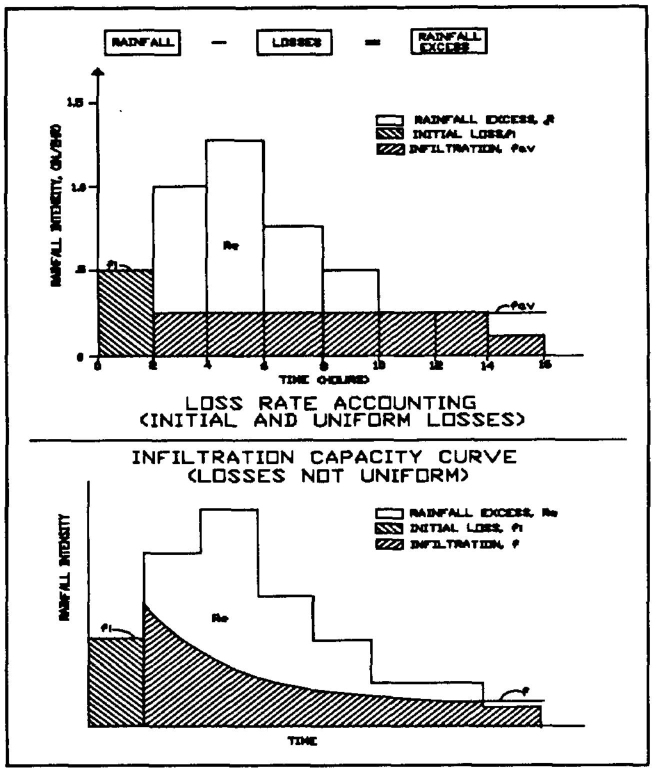

Figure 5-6. Examples of simple loss rate accounting

c. Runoff transformations. After precipitation and loss rate analyses are complete, the engineer is left with an estimated runoff from the watershed expressed in inches per time period for the storm. Runoff in cubic feet per second, rather than (for instance) inches per hour, is needed for hydrograph analysis. Consequently, a transformation is required to obtain runoff quantities in the desired format. Most hydrologic modeling makes this transform using the unit hydrograph technique. Occasionally in highly urbanized catchments, the kinematic wave technique is used. The selection of which technique to use is normally up to the hydrologic engineer.

(1) Unit hydrograph method.

(a) This technique was first developed in the 1930's and is still the predominate technique used in the Corps for a runoff transformation. Many unit hydrograph (UHG) methods are available, with the main ones being the Snyder, Clark and SCS techniques (USACE 1990a). The unit hydrograph technique involves the development of a "pattern" hydrograph, representing the runoff of 1 in. (or unit) of rainfall excess, occurring uniformly during a specified duration (1 hour, 1 day, etc.) over a specified watershed. The assumption is that any other rainfall excess (more or less than 1 in.) during the same duration produces a similar hydrograph with the discharge ordinates proportionally higher or lower than those of the unit hydrograph. Figure 5-7 illustrates this concept.

(b) Preferably, the UHG is derived from recorded rainfall-runoff events recorded at stream gages. These "known" unit hydrographs may be related to measurable basin parameters through regression analyses to determine unit hydrograph parameters at ungaged sites throughout the watershed. This procedure is the same as described in paragraph 4-3. Where no gage data are available, generalized techniques, such as the SCS methods, are appropriate.

(c) The advantages of the unit hydrograph method include: extensive experience with usage, well-documented theory, and applicability to the development and use of regional parameters. The disadvantage is that rainfall excess over the basin is transformed to a discharge hydrograph at the mouth, without specific

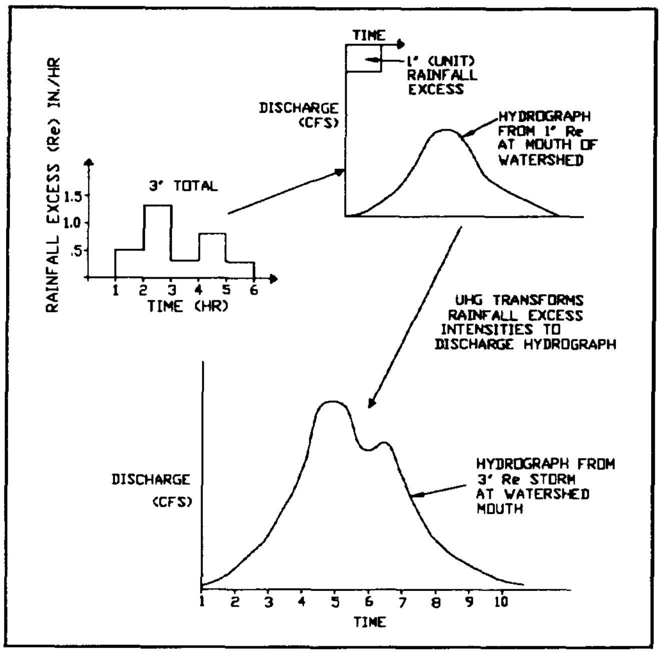

Figure 5-7. Unit hydrograph concept

regional parameters. The disadvantage is that rainfall excess over the basin is transformed to a discharge hydrograph at the mouth, without specific accounting for the movement of runoff over land surfaces. Unit hydrographs may differ somewhat as storm intensities increase; therefore, using the same unit hydrograph for a 2-in. storm and for a 10-in. storm is generally not advisable.

(2) Kinematic wave method.

(a) This technique was developed in the 1950's and attempts to trace the movement of runoff through the watershed to the basin outlet. The main assumption of this technique is that water moves "kinematically," or at the slope of the land surface or channel bottom. This movement is modeled by use of "typical" lengths and slopes for overland flow, collector channels, and the tributary or main channel. Friction values must also be assigned to each element. Figures 5-8 and 5-9 show conceptually the watershed modeling and individual elements used in applying the kinematic wave procedure, respectively.

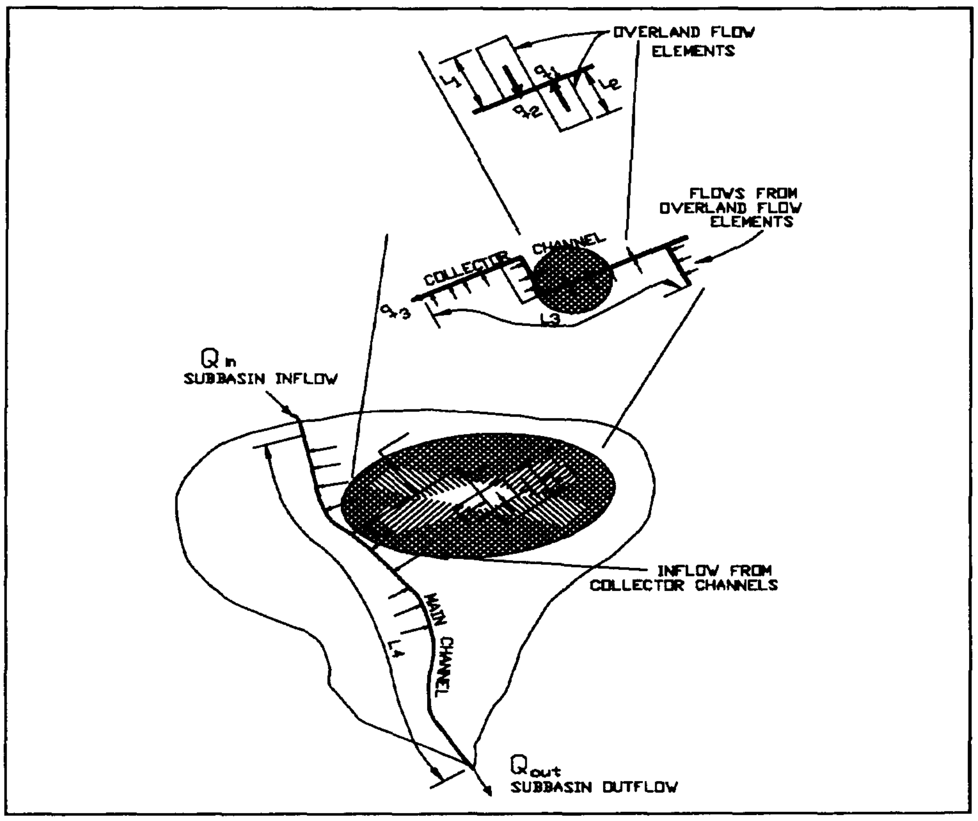

Figure 5-8. Watershed modeling using the kinematic wave method

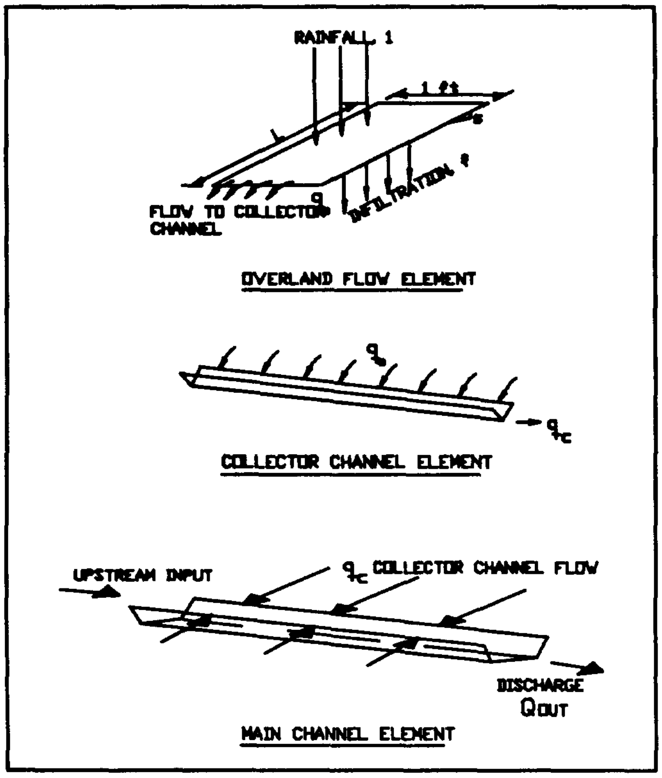

Figure 5-9. Elements used in kinematic wave calculations

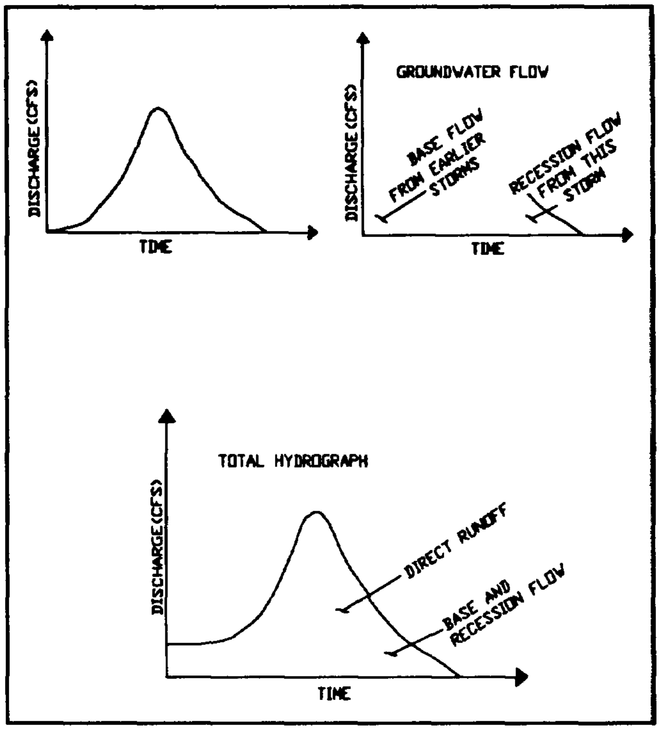

Figure 5-10. Base/recession flow hydrograph components

(b) Application of this procedure requires considerable judgment in selection of appropriate variables for each flow strip and to evaluate the discharge hydrograph output for reasonableness. The advantage of this technique is that it is more physically based and conceptually complete in terms of the physics of runoff. The main disadvantages are difficulty in determining average strip lengths, slopes, and roughnesses, and reduced applicability for low-slope land surfaces and channels.

d. Base flow and recession flow. The preceding discussion focused on rainfall excess and the resulting direct runoff. The resulting discharge hydrograph does not include the streamflow that would have occurred without any rainfall excess, or the water that enters the stream from groundwater flow well after direct runoff has ended. The former inflow is called base flow and the latter is termed recession flow. Figure 5-10 illustrates base and recession flow segments of the total discharge hydrograph. Base and recession flow are relatively small portions of the runoff hydrograph for small watersheds that are sometimes ignored, especially for small urban catchments. These parameters become important as the basin area increases and certainly cannot be ignored for large watersheds.

5-5. Routing Concepts

After the foregoing analysis is complete, a discharge hydrograph has been computed at the outlet of a subarea. This hydrograph moves downstream, combines with otherhydrographs, and moves through the channel and floodplain towards the mouth of the main river. Means of accounting for hydrograph movement is by routing. Routing is simply a method of translating the hydrograph in time and accounting for the hydrograph's change in shape as it moves through the stream system. Hydrologic routing accounts for changes in the time distribution of volume and employs a relatively straightforward computation procedure. Figure 2-12 illustrates the basic concept of hydrologic routing. Hydraulic routing, or unsteady flow computation, is much more difficult to apply and can include the effects of pressure and momentum changes. The application of hydraulic routing requires an engineer with special experience and is further addressed in Chapter 6.

a. Hydrologic routing computations.

(1) Routing techniques. Many techniques are available for hydrologic routing, ranging from simple graphical methods to more complex techniques. These methods include: lag-average, Tatum, Muskingum, Muskingum-Cunge, modified Puls routing and others (USACE 1990a). All methods attempt to account for translation time through the reach and for reach storage. The selection of an appropriate routing procedure depends on the judgment of the engineer, the availability of information to determine routing parameters, and the type of flood damage reduction project under investigation.

(2) Reservoir and Puls routing. The most conceptually complete methods are reservoir (flat pool) and Puls routing. The procedures for both are similar and directly account for the storage available in the routing reach. Figure 5-11 shows the results of a typical reservoir and channel operation. Figure 4-5 shows the routing operation as part of the overall modeling process.

(3) Routing example. Possibly the easiest way to visualize a routing operation is with a reservoir example. A dam constricts the outflow to whatever opening is designed through the dam structure (conduit and spillway). Consequently the inflow hydrograph is largely stored behind the dam and released at a lower rate through the outlet, over a much longer time period. The storage benind the dam and the characteristics of the outlet structure must be known to determine the outflow hydrograph from the dam. A hydrologic analysis of the latter two features will result in a storage versus outflow relationship. This relationship plus the inflow hydrograph can be used to route the inflow hydrograph through storage, determi..ing the outflow hydrograph and the maximum pool stage. This operation is important to determine the adequacy of the spillway discharge capacity and to ensure that the dam is higher than the design pool elevation.

(4) Routing reaches. The subdivision of a total watershed into subareas determines the routing reaches

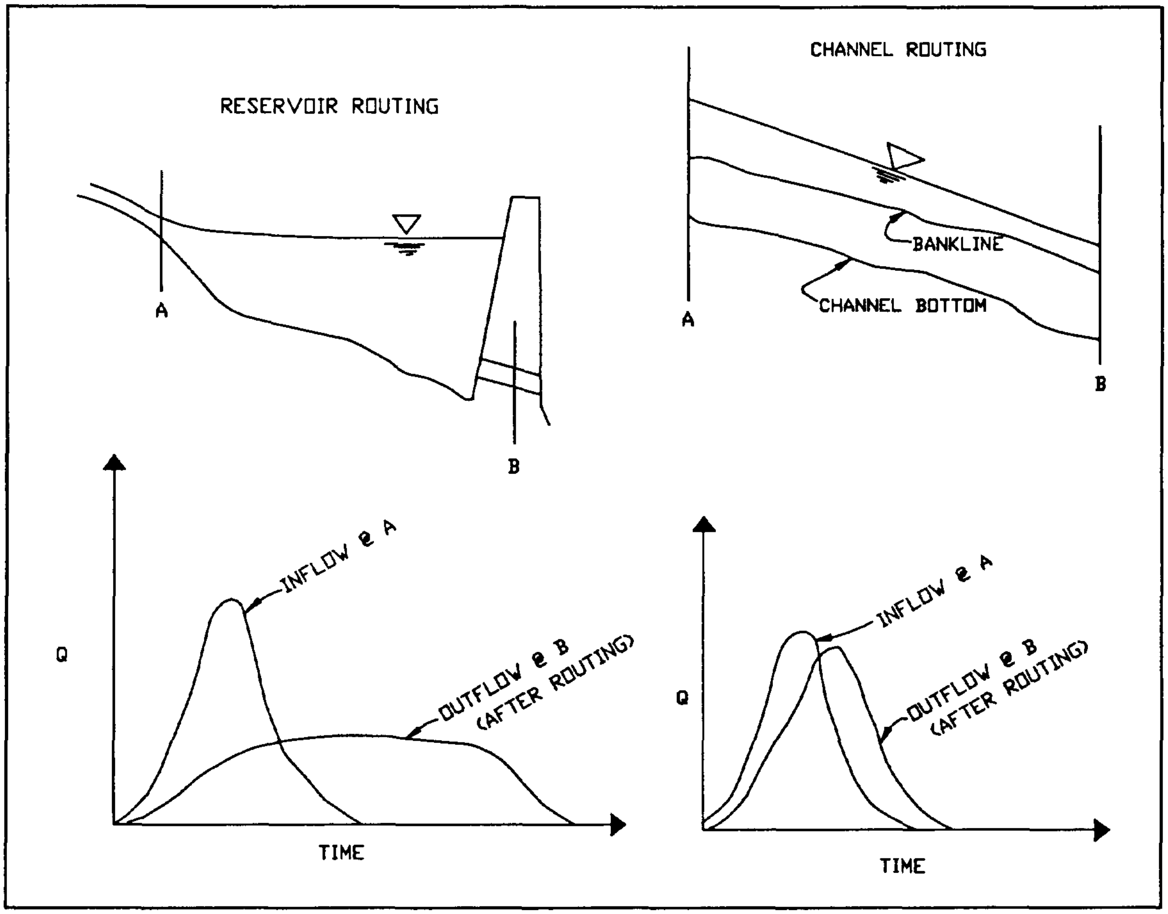

Figure 5-11. Examples of reservoir and channel routing

required. Travel times and storage within these reaches are determined so that routing operations may be carried out and the total hydrograph may be translated downstream. Figure 5-11 shows that reservoir routing greatly affects both timing and shape of the outflow (routed) hydrograph, while channel routing mainly affects the timing of the outflow (routed) hydrograph.

(5) Flood reduction components. Routing studies are important to evaluate the effects of flood reduction components throughout the watershed. Reservoir routings are carried well downstream to evaluate reduced flooding attributable to the structure. Local protection projects (levees and channel modifications) may affect nearby areas adversely by removing or reducing storage available. The magnitude of these changes can only be addressed by routing studies with and without the flood reduction component.

5-6. Calibration of the Model

a. General. All of the foregoing components are incorporated into the overall hydrologic model to simulate discharge hydrographs and determine discharge-frequency relationships throughout the watershed. However, prior to developing this information, the model must be operated for storm-flood events having known input and output to ensure that the model is reproducing actual floods. This process is called "calibration" and is a key part of the total hydrologic modeling process.

b. Calibration process. Historic rainfall from one or more storms is used as input to the total model, which consists of a number of subareas and routing reaches. The model determines losses and rainfall excess, transforms excess to discharge hydrographs, and routes and combines the hydrographs through the watershed. Calculated hydrographs are compared with recorded hydrographs at gage locations in the watershed. When the model reasonably reproduces known hydrographs at the gages, the model is considered to be calculated. If the reproduction of an actual event is poor, one could consider adjusting loss rates, runoff transform coefficients, routing coefficients, etc. (within reasonable limits) to obtain an improved simulation.

c. With calibration, the modeler can have increased confidence that the application of hypothetical (frequency) rainfalls to the model should result in representative runoff hydrographs of that frequency event. Calibration is completed when discharge hydrographs, measured versus calculated, may be compared. Figure 5-12 shows a successful calibration of model output compared to recorded discharge information at a stream gage. In the absence of extensive gaged data, comparison of a calculated peak discharge against that calculated by the regression analyses of paragraph 4-3*c*, or against high-water marks (after calculating a water surface profile with the hydrologic model's output for peak discharge) may be used to calibrate the model.

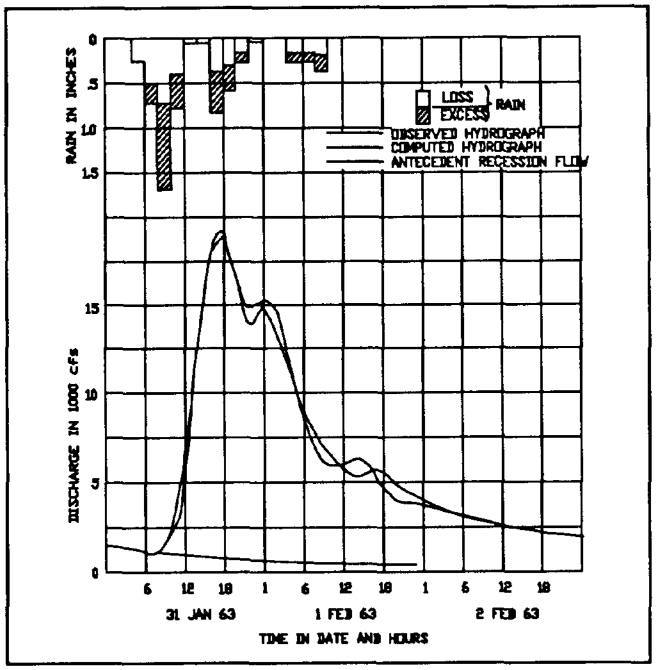

Figure 5-12. Example of a successful calibration

5-7. Verification of the Model

Verification is the final process in hydrologic modeling, after satisfactory calibration has been achieved. Model verification is the process of utilizing additional known data not used in the calibration process to verify that the calibrated model will give good results for unknown storm-flood events. The calibrated model is used with additional historic rainfall to give discharge hydrographs for comparison with gage data. No adjustments of the calibrated model are made in the verification process. The highest level of confidence in model output is achieved when the calibrated model successfully reproduces the known hydrographs with this additional historic data. However, verification is not always possible, as sufficient known storm-flood events may not be available for both calibration and verification.